# Nutrient Enrichment and Marine Ecosystem Disturbance: A Deterministic and Stochastic Analysis

Duncan Knowler, School of Resource and Environmental Management, Simon Fraser University, Vancouver

Abstract. Pollution of the marine areas that support much of the world's commercial fisheries is regarded as a pressing global environmental problem. One often-cited issue is nutrient enrichment, but this may be a mixed blessing: it contributes to primary productivity and increases the sustainable fish catch, while simultaneously causing occasional and damaging ecosystem events. Thus, enrichment's aggregate impact on the economic value of fisheries may be ambiguous. This research develops a method for analyzing such problems, using the example of the Black Sea anchovy fishery. Employing a bioeconomic model that incorporates nutrients directly into fish population dynamics, the problem is formulated in deterministic and stochastic terms and the results compared. The deterministic model assumes that nutrients only contribute positively to fish production for a given ecological state, and ignores stochastic events leading to shifts between states. Accordingly, marginal abatement of nutrients leads to annual welfare losses of US$ 45,000 to 713,00 per µM (1989/90 prices), depending upon the ecosystem state. The stochastic formulation recognizes that planners may have some knowledge of potentially damaging shifts in ecological states, and wish to take this into account. When these shifts are related stochastically to the level of enrichment, nutrient abatement is shown to have an indeterminate welfare effect. However, an experimental empirical analysis indicates that a marginal change in nutrients can generate positive and sizeable aggregate benefits for the Black Sea anchovy fishery under certain conditions. The general applicability of such an approach for analyzing a range of marine environmental problems is noted.

Keywords: marine fisheries, marine environment, nutrient enrichment, anchovy, Black Sea

## 1. INTRODUCTION

Increasing concern has been expressed about the deterioration of coastal environments and particularly the fisheries these ecosystems support. In many of the affected coastal regions, declining natural resource stocks have been a response to disruptions in marine ecosystems, as well as the more familiar problem of overharvesting. Policymakers are already hard-pressed to implement the necessary policies to address the problem because of transboundary issues and socio-economic constraints. In the absence of information about the benefits of marine habitat improvements to help in targeting corrective policies effectively, their task is made even more difficult. This paper addresses one aspect of marine ecosystem management, namely the influence of nutrient enrichment on small pelagic fisheries and the valuation of the benefits of nutrient abatement investments.

A number of studies of marine coastal areas and semi-enclosed seas address the complex interactions of fisheries and nutrient enrichment or eutrophication (Boddeke and Hagel 1991, Caddy 1990 and Silvander and Drake 1989). Of particular interest is the recognition that nutrient enrichment can be a ‘mixed blessing’, enhancing fisheries by augmenting primary productivity but also having more adverse consequences, such as fostering oxygen-suppressing algal blooms or invasions by exotic species. However, most of these studies address the physical dimensions of the problem and few attempt to value the complex consequences of changing nutrient levels in economic terms (an exception is Turner *et al*. 1997). This summary describes a paper that attempts to address this shortfall, by modelling the relationship between small pelagic fisheries and nutrient enrichment.[1]

A key element in the analysis is the distinction between the problem’s deterministic and stochastic elements. The former tends to characterize the direct influence of nutrients on small pelagic recruitment, as nutrient limitations are gradually relaxed under increasing nutrient loads. For a number of small pelagics, this influence has been positive within moderate ranges for nutrient levels (see references above, especially Boddeke and Hagel 1991). More likely to have a negative impact are the occasional ecosystem disturbances cited above (e.g. algal blooms, invasions) that are generally stochastic in nature. Assuming the two influences can occur together results in offsetting impacts on fisheries with no clear aggregate positive or

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[1] The full paper is being submitted to the Journal of Environmental Economics and Management.

negative effect, which contrasts with standard pollution problems.

The paper's first section presents a relatively simple deterministic spawner-recruit model incorporating only the direct and beneficial influence of nutrients on fish recruitment. It captures only the role of nutrients as a habitat input to fish recruitment, as typified in earlier papers concerned with the valuation of habitat change. After solving for the steady state values in the deterministic model, and valuing nutrient inputs using comparative statics techniques, an approach for integrating the more complex and offsetting stochastic effect of nutrients is introduced. Subsequently, the deterministic model is reformulated in stochastic terms and the value of changes in nutrient levels is derived under these more complex ecosystem conditions. The analysis confirms that a 'mixed blessings' type model yields ambiguous welfare results from marginal changes in nutrient levels. To demonstrate the approach empirically, results for the Turkish Black Sea anchovy are presented and compared for both the simple deterministic model and experimentally for the more complex stochastic case.

## 2. A DETERMINISTIC BIOECONOMIC MODEL WITH NUTRIENT ENRICHMENT AND NO ECOSYSTEM DISTURBANCE

The modelling approach begins with a dynamic, deterministic bioeconomic model of the fishery in discrete time (Clark 1990). It assumes a representative ecological regime, so that environmental conditions are constant. The relationship between exploitable adult biomass $X$, harvest $h$ and spawning biomass $S$ can be expressed as:

$$S_t = X_t - h_t \qquad (1)$$

where $t$ denotes the time period in years. With (1) in mind, the exploitable adult biomass in the next period is indicated by the following transition equation:

$$X_{t+1} = \sigma S_t + R(S_t, P_t) \qquad (2)$$

where $\sigma$ is the natural survival rate with $0 < \sigma < 1$, and $R(S,P)$ is the recruitment function. Recruitment is not only a function of spawning biomass, but of nutrients $P$ as well. Next period biomass is determined by the carryover of adults escaping the harvest and by the addition of new recruits. Note that $R_S$ is first > 0 then < 0, and I assume that $R_P > 0$, as discussed earlier. Both assumptions are consistent with recruitment in small pelagics under modest nutrient enrichment (e.g. a Ricker recruitment curve), but other assumptions could be employed too.

If fish demand is perfectly elastic, the economic component of the model comprises the producers' surplus or economic profits $\pi$ generated by the harvest:

$$\pi_t = p h_t - C(X_t, h_t) \qquad (3)$$

where $p$ is the real ex-vessel, fish price determined by a perfectly elastic demand curve. Rearranging (1), the resulting expression $h = X - S$ can be substituted into (3), eliminating the variable $h$. This substitution yields a statement for profits in $X$ and $S$. Assuming the general cost function $C(X,S)$ is separable in these two variables, the profit function can be rewritten as:

$$\begin{gathered} \pi_t = \theta_1(X_t) - \theta_2(S_t) \\ \theta_i^{\prime} > 0, \quad \theta_i^{\prime\prime} > 0 \quad i = 1,2 \end{gathered} \qquad (4)$$

If nutrients are treated as a fixed parameter, ie. $P = \bar{P}$, the planner's problem under the assumption of optimal management can be expressed as:

$$\begin{aligned} & \max \sum_{t=0}^{\infty} \rho^t \pi(X_t, S_t) = \sum_{t=0}^{\infty} \rho^t [\theta_1(X_t) - \theta_2(S_t)] \\ & s.t. \quad X_{t+1} = \sigma S_t + R(S_t, \bar{P}) \\ & with \ 0 \leq S_t \leq X_t, \ and \ S_0, X_0 \ given \end{aligned} \qquad (5)$$

In (5), $\rho$ is the discount term, defined as $1/(1+\delta)^t$, with $\delta$ denoting the appropriate social discount rate. Clark (1990) shows that by manipulation, this type of problem can be simplified to the maximization of the following value function $V(S)$:

$$V(S_t) = \rho\theta_1[\sigma S_t + R(S_t, \bar{P})] - \theta_2(S_t) \qquad (6)$$

The optimal solution is found by taking the first derivative of (6) and setting this equal to zero.

The comparative static effects of marginal changes in the fixed level of nutrient enrichment $\bar{P}$ are elicited via differentiation of the maximized value function $V[S^*(\bar{P})]$. Defining the latter at the optimum level of input usage for a given set of environmental conditions (eg. nutrients ), results in a positive welfare effect. For marginal changes in nutrients taking place under fixed ecosystem conditions (i.e. with no stochastic ecosystem disturbances permitted), this 'within regime' welfare effect would constitute the full impact.

## 3. CHARACTERIZING A STOCHASTIC MARINE ECOSYSTEM DISTURBANCE PROCESS UNDER NUTRIENT ENRICHMENT

As argued earlier, nutrient enriched marine ecosystems may experience disturbances or 'surprises' that are unpredictable and harmful to fish stocks (e.g. algal blooms or invasions). Moreover, random variations in the disturbed state of the marine ecosystem frequently may serve as the trigger mechanism for these events. One means of modelling this process is to allow for the triggering of individual events when some time-varying threshold disturbance level is exceeded. Moreover, the current level of nutrient concentrations $P_t$ can be used as a proxy for the level of disturbance associated with eutrophication at a given point in time. If disturbance events lead to consistently reduced recruitment, then the stock-recruitment relationship during the intervals between events can be approximated by its 'normal' disturbance-free form. In such a case, a stochastic model would describe a sequence of alternating but well-defined ecosystem regimes, with the jumps between regimes triggered by environmental conditions when these exceed a random threshold level.

Capturing the full effects of nutrient enrichment on pelagic recruitment in this more complex world requires incorporation of both the negative stochastic element described above and the beneficial aspects captured in the deterministic model of the previous section, based on $R_P > 0$.

With several simplifying assumptions in mind, a stochastic transition equation equivalent to (2) can be written as:

$$X_{t+1} = \sigma S_t + R^i(S_t, P_t), \quad where \ i = 1 \ or \ 2 \qquad (7)$$

where $R^i(S,P)$ refers to recruitment under state of the world *i* and is a function of spawning biomass *S* and the nutrient concentration *P*. Two states of the world are recognized: either it is between disturbance events and the recruitment function $R^1(S,P)$ prevails, or there is an event and $R^2(S,P)$ is the relevant stock-recruitment relationship. Note that $R^1(S,P) > R^2(S,P)$ over the entire domains of *X* and *P* for any given values for these two variables. As the system shifts between event and non-event conditions, the recruitment relationship governing the anchovy stock 'jumps' from one variant to the other, but retains the direct and positive impact of enrichment on recruitment via the variable *P* ($R_P > 0$).

The stochastic variable in the analysis is the unknown threshold nutrient concentration at time *t* which may trigger a disturbance event, leading to a jump between the two states. This random variable, denoted as $P^*$, is assumed to be distributed over the interval $[0,\infty]$ with a probability density function $f(P^*)$, and is also assumed to be identically and independently distributed over time. The next step links the random threshold $P^*$ with the current level of nutrients $P_t$ and draws on Cropper (1976).

In statistical terms, the stochastic process described in the paper implies that the parameters of the recruitment function are random variables (as is recruitment itself), which are determined jointly by the current level of nutrients $P_t$ and the random variable $P^*$. Additionally, the recruitment function includes the explanatory variable *P* to account for the direct deterministic influence of nutrients on population dynamics. As a result, the current level of phosphates influences population dynamics in two ways, one is direct and deterministic ('within' regime) while the other is indirect and stochastic (regime 'shift').

## 4. VALUING NUTRIENT CHANGES IN THE STOCHASTIC MODEL WITH MARINE ECOSYSTEM DISTURBANCES

Assuming certain conditions for a constant optimal escapement rule are met, the stochastic problem can be solved similarly to the deterministic problem described in the previous section. The problem can be restated as:

$$\begin{aligned} &\max \sum_{t=0}^{\infty} \rho^t \varepsilon\{V(S_t)\} \\ &s.t. \ 0 \leq S_{t+1} \leq \sigma S_t + R^i(S_t, \bar{P}), \ i = 1 \ or \ 2, \qquad (8) \\ &with \ P = \bar{P} \ and \ S_0 \ given \end{aligned}$$

where all variables and functions are as indicated earlier, except for the expectations operator on the value function, $\varepsilon\{V(S)\}$. The problem is characterized by a fixed exogenous level of phosphates $\bar{P}$, but recruitment fluctuates. Note that the inequality constraint requires escapement in any period to be less than or equal to the current level of stock, regardless of the structural form taken by the recruitment function. This condition helps to define the set of feasible controls, ie. the range of values from which a constant optimal escapement solution can be selected.

Expanding the objective function from (8), and applying the rules for taking the expectation of a function of a random variable yields the stochastic counterpart to (6) from the previous section. This problem can be solved for the steady state value of escapement $S^*$.

The welfare effect of a marginal change in the fixed level of phosphates $\bar{P}$ can now be determined for the stochastic case by drawing on the earlier deterministic comparative static analysis. If the demand curve for fish is perfectly elastic, the correct welfare measure is simply the change in producers' surplus, or $d\pi^*/d\bar{P}$. Expanding the expectations expression in the resulting expression and taking the relevant expectation, the deterministic ('within' regime) and stochastic (regime 'shift') elements are isolated in the paper.

Increasing nutrient levels may lead to immediate and tangible fishery benefits, since the 'within regime' effect results in higher equilibrium harvests. At the same time, enrichment creates a potentially offsetting increase in the risk of recurrence of an ecosystem surprise or regime 'shift'. It is not possible to determine which effect will dominate without knowledge of the model's parameter values and the probability distribution governing the random variable $P^*$. Such ambiguity in the theoretical results means that the sign of the aggregate welfare effect of a nutrient abatement policy under a stochastic optimal management regime cannot be determined *a priori*. This result may seem surprising in light of the often expressed belief that nutrient abatement is purely beneficial. It stems from the specification of the model, which recognizes the mixed blessing conferred on the marine system by nutrients.

## 5. AN EMPIRICAL APPLICATION TO BLACK SEA ANCHOVY

As a result of the indeterminacy of key relationships in the previous section, empirical investigation is required. This section produces valuation estimates for a representative small pelagic fishery that has been subject to nutrient enrichment and a stochastic ecosystem disturbance. An applied bioeconomic model of the Turkish Black Sea anchovy fishery is developed, drawing on a previous investigation of the open access situation governing this commercially important fishery (Knowler *et al.* 2000).

Various authors have described a general deterioration in the Black Sea, a fairly typical semi-enclosed marine system subject to a variety of abuses (Mee 1992, Caddy 1990). Environmental and harvesting pressure are thought to have precipitated recruitment failures amongst small pelagics in the late 1980s, despite the boost to productivity provided by dramatically increasing inputs of nutrients. Perhaps the key development was the establishment of the exotic comb jelly *Mnemiopsis leidyi*. While it was likely introduced as a result of ballast dumping, it is believed that high levels of nutrient enrichment may have played a role in opening up a niche for the species. The subsequent pattern of population explosions followed by periods of remission represent the type of stochastic disturbance modelled in the previous section (GESAMP 1997). Anchovy has been the main commercial fish species affected by *Mnemiopsis*, and phosphates have emerged as the nutrient of most interest, its levels showing a statistically significant and positive correlation with anchovy recruitment (Knowler 1999).

Figure 1 describes the relationships characterizing the Turkish anchovy fishery. The key relationship in the model is the recruitment function, which we have previously identified as the conduit through which nutrients (e.g. phosphates) have an impact on fishery productivity and hence on fishing profits.

To undertake the analysis, three general functions contained in the model of the previous section -- two representing variants of the recruitment function [undisturbed, $R^1(S,P)$ and disturbed, $R^2(S,P)$] and the third a cost function – were estimated. The recruitment function was estimated using a structural change model rather than an explicit predator-prey approach, although the two need not be inconsistent.

With the resulting parameters and the appropriate partial derivative (described above), the value of phosphates as an environmental input into fish production can be calculated. Inserting the relevant functional forms and parameter values into the deterministic version of this partial derivative, produces the following estimates of the desired marginal welfare measure under the two states of the world (all figures in US$ 1989/90):

- Enriched conditions without *Mnemiopsis* (undisturbed): US$ 713,000 per year per µM (phosphate unit).

- Enriched conditions with *Mnemiopsis* (disturbed): US$ 45,000 per year per µM.

Not surprisingly, the marginal valuations are positively signed, since increasing nutrients boosts the exploitable surplus for any ecological state, as long as $R_P > 0$. Additionally, the value of nutrients as an environmental input is greatest under the enriched but no-*Mnemiopsis* state (undisturbed) and lowest when *Mnemiopsis* events occur, since the aforementioned effect is strongest here.

As noted in the previous section, a stochastic optimal management formulation can be used to analyse welfare effects when there is a 'mixed blessings' type of nutrient influence with deterministic and stochastic elements. If a probability distribution for the nutrient threshold $P^*$ can be identified, and certain ancillary information about this distribution is known, then it may be possible to derive indicative valuation estimates for the stochastic model. A notional calculation is made in the paper on the assumption that $P^*$ is an exponentially distributed random variable.

## 6. CONCLUSIONS

There is now increasing evidence that nutrient enrichment problems affecting the world's marine areas are complex and not amenable to the simple analytics applied to standard pollution problems. This observation is especially true for small pelagic fisheries that are not vulnerable to the same eutrophication damages that plague benthic species. Instead, nutrient enrichment effects are more complex, comprising deterministic and stochastic elements, as well as having beneficial and harmful aspects. To properly analyse the welfare effects of changes in nutrient levels, as may occur under proposed nutrient abatement policies, requires that this full range of complexity be incorporated into a valuation model. This paper takes on this task using a standard bioeconomic approach, modified for the presence of a nutrient influence on fish recruitment, and then extends this model to include a stochastic disturbance or ecosystem 'surprise'.

In the simple deterministic case, where only the direct and beneficial role played by nutrients is considered, the problem is one of valuing the change in nutrients as would be done for any environmental input into production. In the empirical case study involving Black Sea anchovy, this more conventional representation of the problem yielded marginal values for nutrient inputs of from $45,000 to $713,000 per µM of phosphates (US$ 1989/90), depending on whether the Black Sea ecosystem is in a disturbed or undisturbed state. Here, the value of a marginal increase in nutrients is assumed to be positive, as would be the case with the influence of mangroves on shrimp production, for example. This effect was called the 'within regime' effect to reflect the absence of any possible shift or disturbance in ecological conditions related to nutrient levels. Clearly, this suggests that nutrient abatement is costly, rather than beneficial, for a representative small pelagic fishery.

Theoretical modelling of the more complex 'mixed blessings' situation, where both the beneficial 'within regime' effect described above and a more insidious 'regime shift' effect are included, yielded ambiguous welfare results for the value of nutrient inputs. This result stems from the offsetting influences of these two effects and the possibility that either one may dominate. In terms of the empirical case study, the latter stochastic effect describes the risk of random outbreaks of the comb jelly *Mnemiopsis leidyi*, that reduce anchovy recruitment and the producers' surplus in the fishery.

Making a series of assumptions about how nutrients might be linked with *Mnemiopsis* outbreaks, experimental results for the value of nutrient inputs in this more complex situation were derived. Most importantly, it was found that for at least one set of assumptions, the benefit of marginally abating the phosphate concentration could be positive and high. Thus, it was demonstrated that within a unified analytical framework, the 'regime shift' effect might well dominate the 'within regime' effect. This finding may be expected to have implications for nutrient abatement programs, where nutrients initially appear to be beneficial to certain fish stocks.

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**Figure 1 The Dynamics of Black Sea Fish Production** (Knowler *et al.* 2000)